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Aircraft Carrier Hangar Bay Smoke Removal Tests Conducted Onboard the U.S.S. *Eisenhower* (CVN-69)

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FOREWORD

This report summarizes work performed to review smoke removal and ventilation tactics in aircraft carrier hangar bays. The objective of this test program was to conduct preliminary scoping tests onboard the U.S.S. *Eisenhower* (CVN-69) for the purpose of providing clarification of the smoke removal procedures described in the NATOPS Firefighting Manual.

During these preliminary scoping tests, smoke generators onboard the U.S.S. *Eisenhower* (CVN-69) were used to determine the smoke filling time and removal performance from the hangar bay, and visibility within the hangar bay used as the measure of performance. The effect of door status and wind direction was also evaluated during these tests. Doors used included elevator doors and other doors opening to weather (i.e., sponson doors). The effect of crosswinds and headwinds was evaluated for the different door configurations.

This report was reviewed for technical accuracy by Eric Wilson.

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(U) The objective of this test program was to conduct preliminary scoping tests onboard the U.S.S. *Eisenhower* (CVN-69) for the purpose of providing guidance on changes to the smoke removal procedures described in the current fire fighting doctrine.

(U) During these preliminary scoping tests, existing smoke generators onboard the U.S.S. *Eisenhower* (CVN-69) were used to determine the smoke filling time and removal performance from the hangar bay under various door configurations, with visibility within the hangar bay used as the measure of performance. The effect of door status and wind direction was evaluated during these tests. Doors used included elevator doors and other doors opening to weather (i.e., sponson doors). The effect of crosswinds and headwinds was evaluated for the different door configurations.

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This test program could not have been accomplished without the cooperation and support of the officers and crew of the U.S.S. *Eisenhower* (CVN-69). CWO2 Livingston's efforts as the team's sponsor ensured that the team was berthed, fed, and comfortable, and had all necessary paperwork to allow them on board. Senior Chief Knauber and Chief Jordan and their hangar deck crew ensured that all necessary equipment was in place and kept operational throughout the testing period. Thanks also to CDR Smolana, Air Boss; CDR Galanie, Mini Boss; Lt. Harrison, Aircraft Handling Officer; and Lt. Fudge, V-1 Division Officer. All personnel involved took an active interest in the successful completion of the testing; their inputs were invaluable to the test program.

INTRODUCTION

Current U.S. Navy firefighting doctrine requires that in the event of a fire in the hangar bay of an aircraft carrier, all fire and elevator doors be closed immediately (NATOPS Manual, Reference 1). This contains the fire, minimizes the introduction of fresh air (which could increase the fire growth), and prevents further fire spread to unaffected areas of the ship. However, closing the elevator and division doors allows smoke and heat to accumulate within the hangar bay, severely reducing visibility for firefighting personnel. Reduced visibility results in disorientation and deterioration of communications among the ship's crew, in addition to reduced firefighting performance.

Additional ventilation guidance is provided in Reference 1, Chapter 7, Section 7.7.7 (as a note) stating, " . . . Cross ventilate to facilitate venting of smoke. Utilize ship's direction to maximize ventilation efforts." This note, and its placement in the procedures, leaves the doctrine open to opposing interpretations: (1) that the promoted ventilation take place while firefighting operations are being performed (i.e., active desmoking), or (2) that the promoted ventilation take place after the fire's been extinguished. As presented, this has led to variable Fleet approaches to a hangar bay fire threat. This guidance is confusing because "cross ventilate" implies opening doors to facilitate the venting of smoke out of the fire space. Considering that the elevator doors are normally open to some degree in good weather, closing doors only to open them later is contradictory. Additionally, previous editions of the NATOPS manual have provided the option of opening one elevator door approximately 3 feet to facilitate the venting of smoke. This provision is currently specified in Chapter 8, Section 8.7.6, for amphibious aviation ships (LPH/LHA/LHD) with similar features. Inconsistencies in this guidance necessitated tests to determine the appropriate door setting to maximize ventilation.

The effects of reduced visibility on firefighter performance have been observed in a number of manned tests conducted in small, below deck spaces onboard the Navy's full-scale research, development, test, and evaluation (RDT&E) facility (ex-U.S.S. *Shadwell*, located in Mobile, Alabama; References 2 through 5) and during an actual fire involving hazardous materials onboard the U.S.S. *George Washington* (CVN-73) (Reference 6). Testing conducted onboard the *Shadwell* followed current doctrine, with the mechanical ventilation system secured upon report of the fire. In these tests, the Fleet participants were unable to perform firefighting operations (dressing out, advancing hose lines, extinguishing the fire, and maintaining boundaries) due to the intense heat and reduced visibility. In the aircraft carrier hangar bay fire, all doors were closed during firefighting operations (per doctrine), resulting in heavy smoke, heat accumulation, and reduced visibility. The reduced visibility and excessive heat hampered firefighting efforts by preventing the fire teams from finding the hose lines, reaching the seat of the fire for an extended period of time, and extinguishing the fire (Reference 6).

Previous testing demonstrated the effectiveness of establishing ventilation pathways, using natural and mechanical ventilation, to remove heat and smoke from the fire space during firefighting operations (References 2 through 5). In a hangar bay, opening the doors may permit venting of the fire space, restoration of visibility, and lowering of the heat threat within the hangar bay. Additionally, natural crosswinds created by changing the course and speed of the ship,

and opening port-side weather doors, may further aid in the smoke and heat removal process. In order to determine whether this should be a recommended practice, actual ventilation testing was conducted onboard the *Eisenhower*.

OBJECTIVE

The objective of this test program was to conduct preliminary scoping tests onboard the *Eisenhower* for the purpose of providing guidance on changes to the ventilation procedures described in the current doctrine. The test results were also used to determine if further testing would be required in order to support further changes to the doctrine.

APPROACH

During these preliminary scoping tests, existing smoke generators onboard the *Eisenhower* were used to determine the smoke filling time and removal performance from the hangar bay under various door configurations, with visibility within the hangar bay used as the measure of performance. The effect of door status and wind direction was also evaluated during these tests. Doors used included elevator doors and other doors opening to weather (i.e., sponson doors). The effect of crosswinds and headwinds was evaluated for the different door configurations.

HANGAR BAY TEST SETUP

In order to evaluate ventilation options unique to each hangar bay, testing was conducted in each of the three hangar bays during this test series. Smoke generators filled the hangar bay with smoke (i.e., "cold smoke"), and the effectiveness of smoke control was assessed for different door configurations. Effectiveness was measured by the ability to see visibility targets located at varying distances from observers. Fleet participants from the *Eisenhower* assisted in the test setup, participation, and cleanup.

U.S.S. *EISENHOWER* (CVN-69) HANGAR BAYS

Nimitz-class aircraft carriers have three hangar bays located on the Main deck, spanning from Frame (FR) 64 to FR 235 and nearly the entire ship's width. The bays are separated by division doors that function as both fire and ballistic doors. The division doors are located at FR 128 and FR 180 and are each two frames thick when nested in a fully retracted position. Hangar Bay 1 has one elevator door (El 1) located on the starboard side of the ship and two sponson doors located on the port side leading to weather via the *Eisenhower*'s smoking pit. Hangar Bay 2 also has one starboard-side elevator door (El 2), but does not have any port-side access to weather. Hangar Bay 3 has two elevator doors: El 3 is located on the starboard side and El 4 is located on the port side. When in a fully open configuration, the elevator doors require

approximately 42 seconds to fully close; the division doors require approximately 18 seconds. While small, portable box fans are available on the ship, there is no fixed means of mechanical ventilation in the hangar bays. To provide this ventilation, one or more of the hangar bay doors are typically one-quarter open, weather permitting.

Testing was conducted in each hangar bay onboard the *Eisenhower*. The hangar bays were minimally cluttered during the testing (i.e., no parked aircraft), with only normal support equipment and materials being stored in each hangar bay. In Hangar Bay 1, a number of tow vehicles, a P-25 Mobile Fire Fighting Vehicle (MFFV), forklifts, and other hangar bay related equipment were stored in the forward third of the bay. A large heating, ventilation, and air conditioning (HVAC) duct unit filled approximately the forward third of the bay overhead. This resulted in a volume reduction for Hangar Bay 1 of approximately one-third. Hangar Bay 2 was relatively open, with only two weapons elevators located along the starboard outboard bulkhead, one forward and one approximately mid-length. In Hangar Bay 3, two pairs of stacked boats (launches) were stored in the aft part of the hangar bay, one pair along the port side and one pair along the starboard side. A significant quantity of supplies (pallets, cardboard boxes, etc.) was located between the boats. These items occupied a volume of approximately 17 meters (m) (57 feet (ft)) deep by the full hangar width and height. Based on the storage of materials and equipment in the hangar bays, the gross and net volumes of each hangar bay were calculated as shown in Table 1. The calculation for the net volume of Hangar Bay 2 took into account the reduced volume from the two weapons elevators: 3,644 m^3 (12,870 ft^3) for the forward elevator and 3,940 m^3 (13,912 ft^3) for the aft elevator. The dimensions of each hangar bay were based on frame measurements, with each frame being 1.2 m (4 ft) on center.

TABLE 1. Hangar Bay Volumes.

Hangar bay no.	Length, m (ft)	Width, m (ft)	Height, m (ft)	Gross volume, m^3 (ft^3)	Net volume, m^3 (ft^3)
1	52 (170)	32 (106)	8.5 (27.5)	14,100 (495,500)	9,400 (330,300)
2	63 (208)	32 (106)	8.5 (27.5)	17,100 (606,300)	9,600 (337,300)
3	50 (163)	32 (106)	8.5 (27.5)	13,600 (475,100)	9,000 (309,000)

HAZARD CALCULATIONS

To provide an indication of the effect of a worst case fire scenario in a hangar bay, a flammable liquids spill fire from an aircraft in a hangar bay with all doors closed was modeled. A fuel spill could develop from a number of sources, such as a ruptured fuel tank (a wing of one plane clips another or a tow vehicle hits a belly tank) or a fueling line break (dumping fuel onto the deck). The size of a fuel spill in an aircraft hangar bay is dependant on the size of the rupture, the amount of fuel available to spill, the roll of the ship, and the actions of the crew to secure the leak. Based on these variables, it is plausible to assume that a fuel spill could develop and cover an area roughly the size of an aircraft. This would result in a fuel spill approximately 6 to 9 m (20 to 30 ft) long by 6 m (20 ft) wide, or approximately 46 m^2 (500 ft^2). A 46-m^2 (500-ft^2) JP-5 pool fire would produce unimpeded flames approximately 16 m (52 ft) high and would produce a fire with a free burning heat release rate of approximately 108 megawatts (MW)

(102,000 BTUs per second (BTUs/s)). Using the hangar dimensions provided in Table 1 (length and width), smoke and heat produced from a fire of this size would descend down to approximately 1.5 m (5 ft), the average head height of an adult, in as little as 3 minutes. The smoke filling calculation was performed using the FPETOOL computer calculation package (Reference 7). The fire was input assuming a linear fire growth to the maximum size in 60 seconds.

SMOKE GENERATORS

Smoke was introduced into each hangar bay using Rosco 1600 Fog Machines with Rosco Fog Fluid. All smoke generators were owned, operated, and maintained by *Eisenhower* personnel. In the first test, four smoke generators were positioned in an area roughly representing the plan area of a parked aircraft. The smoke generators were pointed inward for this test, resulting in a "plume" that rose to the overhead and banked down. It took approximately 40 to 45 minutes to fill the hangar bay with smoke using four smoke generators. The filling time was defined as the time from the start of the test to the time for all visibility observers to lose sight of their targets or for the test director to determine that a sufficient quantity of smoke was present in the hangar bay. To decrease the fill time of the hangar, all subsequent tests utilized six smoke generators. The smoke generators were repositioned to project the smoke outward, resulting in a larger "plume" and a quicker filling time of approximately 30 minutes. In cases where visibility of certain targets was not lost, because of the location or configuration of the hangar bay, a decision was made by the test director to commence ventilation rather than to delay the test. Typically in these cases, the entire hangar bay was filled with a sufficient amount of smoke to allow observations of the ventilation performance.

VISIBILITY TARGETS

To determine the effectiveness of each particular ventilation configuration, four visibility targets were utilized per test. Targets were selected on the bulkheads opposite the starboard-side elevator door, and near the fore and aft end bulkheads/division doors. Visibility targets of interest included a standard commercially available "Exit" sign, red fire equipment storage lockers, first aid boxes (red cross on a white background), purple JP-5 fueling lines at fueling stations, a green eye-wash station, and yellow plastic storage/shipping containers. The exit sign was used in all tests as a standard visibility target because of its portability and high contrast. During one test, distress marker strobes were utilized for additional visual information.

Each observer was assigned a number that was called out when visibility was first lost and again when visibility was recovered. During Test 1, the observers were seated in folding chairs positioned 3 m (10 ft) and 6 m (20 ft) from their respective targets. Review of the test results showed that visibility was not lost by the observers seated 3 m (10 ft) from their target. Therefore for all subsequent tests, the observers were seated 6 m (20 ft) and 9 m (30 ft) from their respective targets. Two observers were seated at each location, one *Eisenhower* crew member and one member of the test team.

TEST PROCEDURE

Prior to the start of each test, all elevator doors, division doors, and personnel doors around the perimeter of the appropriate hangar were closed. Safety monitors (Fleet personnel) were positioned at each personnel door, on the outside of the hangar bay, to prevent non-test personnel from entering the space during a test. Fleet personnel were available to operate elevator and division doors as requested by the test director.

A prebrief was conducted prior to the start of each test to detail the anticipated hangar bay conditions, to review the call-out procedure for visibility of the targets, and to explain the anticipated door configuration to be evaluated. Once all visibility targets, observers, and hangar bay doors were set, the test director announced the start of the test and all smoke generators were started. As the hangar bay filled with smoke, the observers were instructed to notify the test director after their target became obscured for more than 5 seconds. When all targets were obscured, or the test director determined that the conditions were sufficient to initiate the door configuration, Fleet personnel coordinated with the bridge to achieve the desired ambient wind conditions (i.e., crosswind or headwind). Upon achieving the desired outside wind conditions (or as close as possible), the particular door configuration was initiated to begin clearing smoke from the hangar bay. When the visibility increased to the point that the visibility targets could be seen, the observers notified the test director. The smoke generators continued to produce smoke as the doors were opened, simulating a fire that was still burning (i.e., "active desmoking").

When the effects of the particular door configuration had been demonstrated, the test was terminated, all division and hangar bay doors were opened, and all hangar bays were cleared of smoke in preparation for the next test. During our test series, significant smoke leakage around and between division doors was noted by both our test team and the ship's personnel. When running tests back to back in the same hangar bay, the test area was not fully cleared of smoke between tests to minimize the test turnaround time. Because the performance of each ventilation configuration was based on the initiation of the door configuration, residual smoke in the hangar bay had no effect on test results.

VISIBILITY RECOVERY CALCULATION PROCEDURE

The measure of effectiveness of each door configuration was the time required for visibility to be recovered. Ventilation was considered initiated at the initial opening of the elevator doors and/or personnel door(s) and was taken as time 0:00. The effectiveness of the particular door configuration (in minutes) was taken as the time at which 75% of all observers who lost visibility had recovered it. This procedure normalized the varying visibility recovery times for each observer and each position to allow comparison of all results. For example, if ventilation was initiated at 30 minutes and a particular observer regained target visibility at 38 minutes, ventilation effectiveness was calculated to be 8 minutes for that particular observer location. In a number of instances, observers reported losing and regaining visibility of their targets multiple times over a short period of time (a couple of minutes). When this occurred, the time to lose visibility

was taken as the first time visibility was lost. The last time visibility was regained then became the visibility recovery time.

TEST RESULTS

Seven tests were conducted onboard the U.S.S. *Eisenhower* (CVN-69) during the period of 21–23 January 2000. These tests evaluated the effect of opening various doors (elevator and personnel) under a headwind or crosswind. During each test, the leeward elevator door was held open 1 m (3 ft) for approximately 5 minutes before other changes were made. Port-side sponson doors were opened to create cross ventilation. Table 2 provides the general objective of each test and the test matrix for all tests conducted. Because each of the three hangar bays is uniquely configured, test results for each hangar bay are discussed separately. A time line for each test, including visibility observer results and door sequencing, is included as the Appendix to this document.

TABLE 2. Hangar Bay Ventilation Test Matrix and General Results.

Test no.	Hangar bay no.	Test objective	Wind direction/speed (as reported by the bridge)	General results
1	3	Evaluate effect of crosswind when attempting to ventilate Hangar Bay 3	20-knot port crosswind	Combination of crosswind and two opposite side ships doors resulted in quick removal of smoke.
2	1	Evaluate effect of crosswind when attempting to ventilate Hangar Bay 1	Port crosswind	Opening port-side sponson doors allowed a crosswind to quickly ventilate hangar bay.
3	1	Evaluate effect of headwind when attempting to ventilate Hangar Bay 1	30-knot headwind/10-knot crosswind	Headwind had little effect on ventilating hangar bay. Ventilation time approximately twice as long when compared to crosswind test (Test 2).
4	2	Evaluate effect of headwind when attempting to ventilate Hangar Bay 2	21-knot headwind	Hangar bay configuration did not assist in ventilating smoke quickly. Hangar bay configuration will lead to difficulties in ventilating smoke during a fire event. Headwind had little effect on smoke in hangar bay.
5	3	Evaluate effect of headwind when attempting to ventilate Hangar Bay 3	20-knot headwind/2-knot crosswind (starboard to port)	Headwind had little effect on ventilating hangar bay. Ventilation time approximately twice as long compared to crosswind test (Test 1).
6	3	N/A	N/A	Invalid test.
7	3	Evaluate effect of crosswind when attempting to ventilate Hangar Bay 2	28-knot headwind/8-knot port crosswind	Hangar bay configuration did not assist in ventilating smoke quickly. Hangar bay configuration will lead to difficulties in ventilating smoke during a fire event. Crosswind had little effect on smoke in hangar bay.

HANGAR BAY 1

Tests 2 and 3 were conducted on 22 January 2000 to simulate the smoke conditions from a fire in Hangar Bay 1. Test 2 utilized a port to starboard crosswind to evaluate the ventilation effectiveness of opening the elevator door and the two port-side sponson doors leading directly to weather. Test 3 evaluated the effectiveness of the same door configuration under a headwind scenario. Figure 1 provides a plan view of Hangar Bay 1 for Tests 2 and 3, showing the location of the observers and visibility targets, smoke generators, elevator door, and port-side sponson doors.

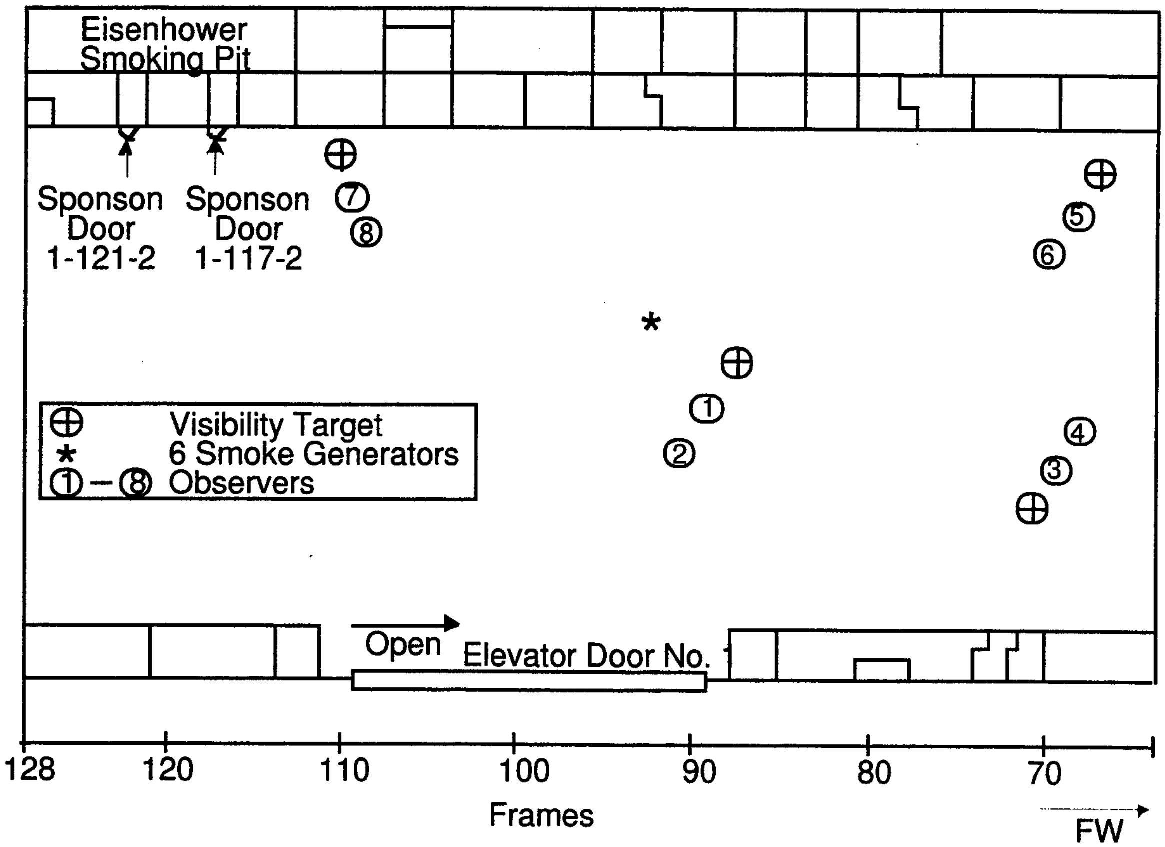

FIGURE 1. Setup for Hangar Bay 1 Smoke Testing.

TEST 2 RESULTS (CROSSWIND TEST OF HANGAR BAY 1)

Test 2 was conducted on 22 January 2000 with a port crosswind (magnitude not recorded), which was established prior to opening any doors. The hangar bay was sufficiently filled with smoke at 30 minutes and the door sequencing commenced. At this time, four of the eight observers had already reported losing visibility of their targets. Table 3 provides the calculation of ventilation effectiveness for the door configurations tested. Table 4 summarizes the door configuration effectiveness. The smoke generators were secured at 62 minutes.

The results presented in Tables 3 and 4 document that it took approximately 10 minutes for 75% of the observers to regain visibility when the elevator door was opened halfway and both port-side doors were open. Observations of smoke movement showed that the external

crosswind resulted in fresh air being brought into the hangar through the port-side sponson doors and exiting out the elevator door as expected. Even with the port-side doors located in the aft port corner of the hangar bay, visibility was regained by most of the observers located in the forward part of the hangar, approximately 46 m (150 ft) away. The current baseline ventilation doctrine for amphibious aviation type ships (open elevator door approximately 1 m (3 ft)) was ineffective, as no observers regained visibility of their targets.

TABLE 3. Test 2 Ventilation Effectiveness Per Observer.

Time, min.	Door condition	Observer status, visibility lost[a]	Observer status, visibility regained	Ventilation effectiveness, min.
0	Elevator door closed, both port-side doors closed			
30		5, 6, 7, 8		
32		1, 2, 4		
34	Elevator door open 3 ft	3	6	4
36	Elevator door open 3 ft, aft port-side door open		5	6
42	Elevator door half open, both port-side doors open		3 1, 2, 4	8 10
48	Elevator door full open, both port-side doors open		7, 8	18
50	Test end			

[a] Time to visibility lost is taken as time ventilation commenced if visibility was lost prior to opening the hangar bay doors; otherwise it is taken as actual time visibility lost.

TABLE 4. Test 2 Ventilation Effectiveness Summary.

Ventilation effectiveness, min.	Visibility recovery, %	Cumulative observer no.	Door condition at recovery
0			Begin test
4	13	6	Elevator door open 3 ft
6	38	6, 5	Elevator door open 3 ft, aft port-side door open
10	75	1, 2, 3, 4, 5, 6	Elevator door half open, both port-side doors open
18	100	1, 2, 3, 4, 5, 6, 7, 8	Elevator door full open, both port-side doors open

TEST 3 RESULTS (HEADWIND TEST OF HANGAR BAY 1)

Test 3 was conducted on 22 January 2000 with a 30-knot headwind and a 10-knot port crosswind achieved prior to opening any doors. The hangar bay was sufficiently filled with smoke at 32 minutes and the door sequencing commenced. By this time, seven of the eight

observers had already reported that they lost visibility of their targets. Table 5 provides the calculation of ventilation effectiveness for the door configurations tested. Table 6 summarizes door configuration effectiveness. The smoke generators were secured at approximately 60 minutes.

The results presented in Tables 5 and 6 document that it took approximately 16 minutes for 75% of the observers to regain visibility. At this time, the elevator door was fully opened and both port-side sponson doors were open. Observations of smoke movement showed that the headwind created a "puffing" condition at each of the doors (elevator and sponson doors). The lack of a developed inflow or outflow condition at each door resulted in a longer recovery time and the need for the elevator door to be fully opened.

TABLE 5. Test 3 Ventilation Effectiveness Per Observer.

Time, min.	Door condition	Observer status, visibility lost[a]	Observer status, visibility regained	Ventilation effectiveness, min.
0	Elevator door closed, both port-side doors closed			
32		2, 3, 4, 5, 6, 7, 8		
34		1		
38	Elevator door open 3 ft, both port-side doors open		1	4
40	Elevator door open 3 ft, aft port-side door open		8	8
46	Elevator door half open, both port-side doors open		3, 7	14
48	Elevator door full open, both port-side doors open		2, 4	16
50	Elevator door full open, both port-side doors open		5, 6	18

[a] Time to visibility lost is taken as time ventilation commenced if visibility was lost prior to opening the hangar bay doors; otherwise is it taken as actual time visibility lost.

TABLE 6. Test 3 Ventilation Effectiveness Summary.

Ventilation effectiveness, min.	Visibility recovery, %	Cumulative observer no.	Door condition at recovery
0			Begin test
8	25	1, 8	Elevator door open 3 ft, both port-side door open
14	50	1, 3, 7, 8	Elevator door half open, both port-side doors open
16-18	100	1, 2, 3, 4, 5, 6, 7, 8	Elevator door full open, both port-side doors open
20			End test

HANGAR BAY 2

Test four evaluated ventilation effectiveness utilizing only the elevator door under a headwind condition. Figure 2 provides a plan view of Hangar Bay 2 for Test 4, showing the location of the observers and visibility targets, smoke generators, and the elevator door.

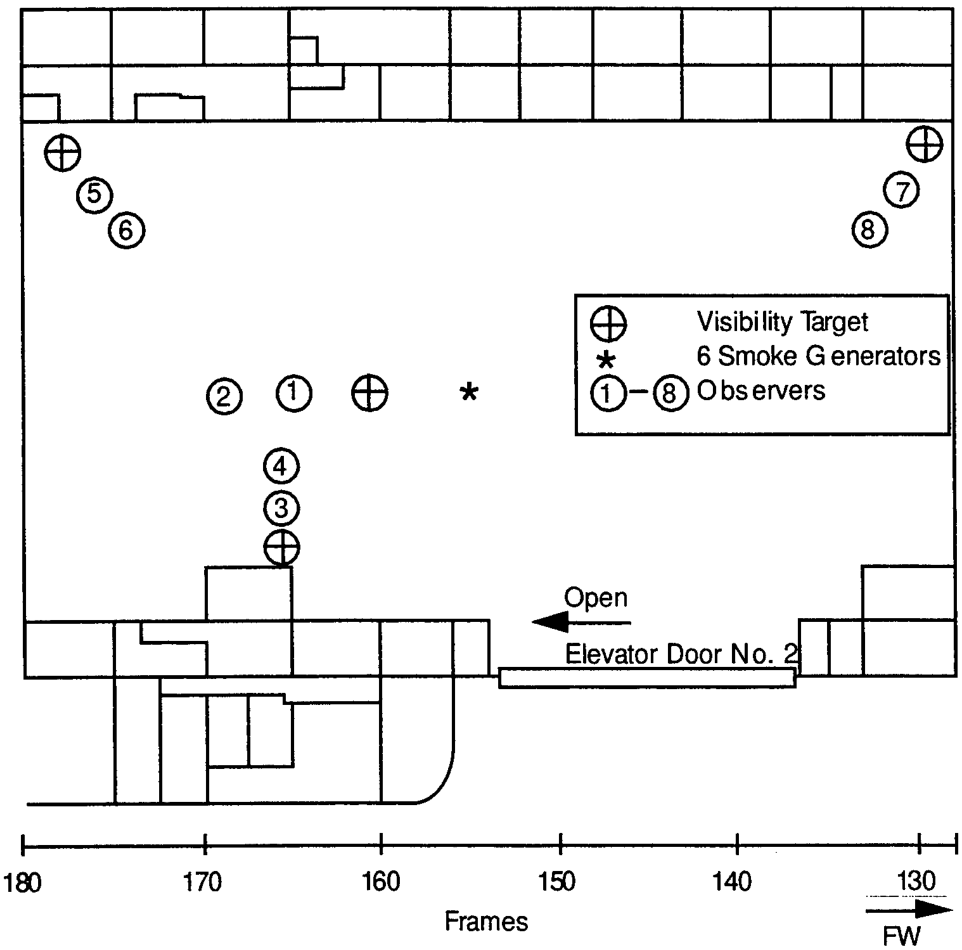

FIGURE 2. Setup for Hangar Bay 2 Smoke Testing.

An additional test item was set up during Test 4, a strobe marker to possibly locate hose and fire stations. The strobe was visible from a distance greater than 6 m (30 ft) during the worst case smoke conditions. The use of three SDU-5/E distress light markers proved that a strobe can be seen through the smoke and therefore could be developed into a possible fire station marker. A red lens is recommended.

TEST 4 RESULTS (HEADWIND TEST OF HANGAR BAY 2)

Test 4 was conducted on 22 January 2000, with a 21-knot headwind when ventilation commenced. Power was lost in Hangar Bay 2 at 22 minutes due to ongoing engineering drills, however the hangar bay contained a sufficient amount of smoke to continue the test. Because of the power loss, the exit sign also went out. Therefore the data from the two observers watching

the exit sign (observers 1 and 2) were not used in the analysis. When the doors were opened, observers 6, 7, and 8 had already reported that they lost visibility of their targets. Table 7 provides the calculation of ventilation effectiveness for the door configuration tested, and Table 8 summarizes door configuration effectiveness. The test was terminated at approximately 40 minutes.

The results presented in Tables 7 and 8 indicate that opening the elevator door fully had minimal impact on ventilation. Visual observations also confirmed that there was minimal smoke movement out the elevator door, corroborating the results from the observers.

TABLE 7. Test 4 Ventilation Effectiveness Per Observer.

Time, min.	Door condition	Observer status, visibility lost[a]	Observer status, visibility regained	Ventilation effectiveness, min.
0	Elevator door closed			
26		6, 7, 8		
30	Elevator door half open		7	4
32	Elevator door full open		6	6
	N/A, did not recover		8	N/A

[a] Time to visibility lost is taken as time ventilation commenced as visibility was lost prior to opening the hangar bay doors.

TABLE 8. Test 4 Ventilation Effectiveness Summary.

Ventilation effectiveness, min.	Visibility recovery, %	Cumulative observer no.	Door condition at recovery
0			Begin test
4	33	7	Elevator door half open
6	67	6, 7	Elevator door full open

HANGAR BAY 3

Tests 1, 5, and 7 were conducted to simulate smoke conditions from a fire in Hangar Bay 3. Hangar Bay 3 is unique in that there are two elevator doors, one on the port side (El 4) and one on the starboard side (El 3). Test 1 evaluated ventilation effectiveness utilizing the elevator doors under a crosswind condition. Test 5 was conducted to simulate the effectiveness of evacuating smoke from the hangar bay under a headwind condition. No visibility observers were utilized in Test 7 and only subjective smoke movement observations were made. Figure 3 provides a plan view of Hangar Bay 3 for Tests 1, 5, and 7, showing the location of the observers and visibility target, smoke generators, and elevator doors.

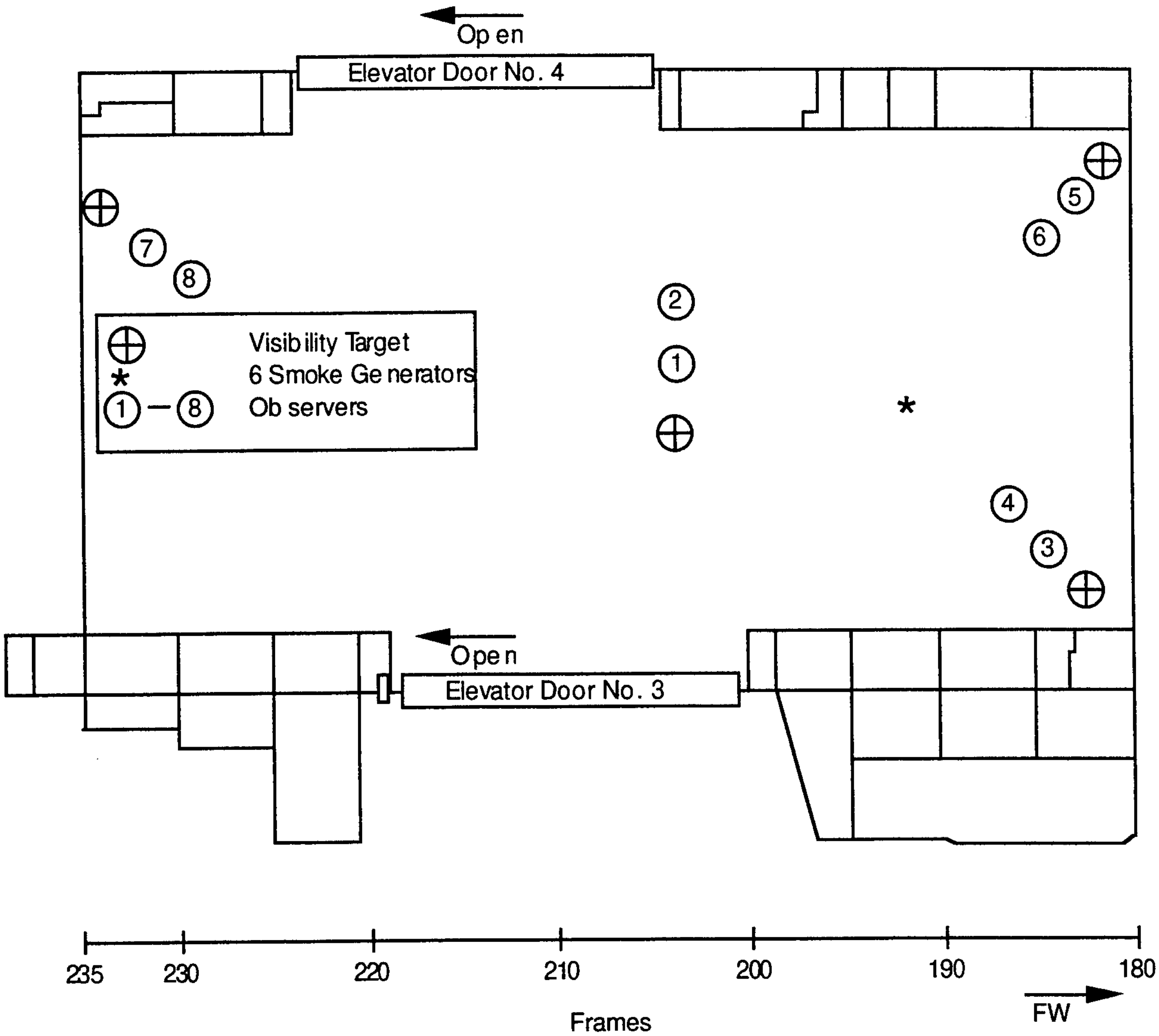

FIGURE 3. Setup for Hangar Bay 3 Smoke Testing.

TEST 1 RESULTS (CROSSWIND TEST OF HANGAR BAY 3)

Test 1 was conducted on 21 January 2000 with a 20-knot port crosswind when ventilation commenced. The hangar bay was sufficiently filled with smoke at approximately 45 minutes (only four smoke generators used), and the ventilation sequencing commenced. When the hangar doors were opened, three of the eight observers had already reported losing visibility of their targets (recall that the observers for this first test in the series were spaced at 10 and 20 ft from their visibility target–later tests had observers farther away to more quickly present the required test condition). Table 9 provides the calculation of ventilation effectiveness for the door configuration tested. Table 10 summarizes the door configuration effectiveness. The smoke generators were secured at 62 minutes.

The results presented in Tables 9 and 10 document that it took approximately 8 to 10 minutes for the observers to regain visibility of their targets. At this time the windward door (El

4) was open approximately 1 m (3 ft) and the leeward door (El 3) was open approximately halfway. The results generated in this test are similar to the crosswind tests conducted in Hangar Bay 1 (Test 2), where the smaller openings were located on the windward side of the ship and the larger opening was located on the leeward side of the ship. When both elevator doors were opened fully, it was noted visually that the strong wind moving through the hangar bay stripped the smoke out of the middle third of the hangar bay (directly between the two open doors). However the door configuration had little effect on removing smoke from either the forward or aft third of the hangar bay.

TABLE 9. Test 1 Ventilation Effectiveness Per Observer.

Time, min.	Door condition	Observer status, visibility lost[a]	Observer status, visibility regained	Ventilation effectiveness, min.
0	Elevator door closed, both port-side doors closed			
44		4, 6		
50		2		
52	El 3 open 3 ft, El 4 open 3 ft		2	2
			4	8
54	El 3 full open, El 4 open 3 ft		6	10
56	Test end			

[a] Time to visibility lost is taken as time ventilation commenced if visibility was lost prior to opening the hangar bay doors; otherwise it is taken as the actual time visibility was lost.

TABLE 10. Test 1 Ventilation Effectiveness Summary.

Ventilation effectiveness, min.	Visibility recovery, %	Cumulative observer no.	Door condition at recovery
0			Begin test
8	67	2, 4	El 3 open 3 ft, El 4 open 3 ft
10	100	2, 4, 6	El 3 full open, El 4 open 3 ft

TEST 5 RESULTS (HEADWIND TEST OF HANGAR BAY 3)

Test 5 was conducted on 23 January 2000, with a 20-knot headwind and a 2-knot starboard to port crosswind when ventilation commenced. The hangar bay was sufficiently filled with smoke at approximately 30 minutes, and the ventilation sequencing commenced. At the time the doors were opened, all eight observers had already reported losing visibility of their targets. Table 11 provides the calculation of ventilation effectiveness for the door configuration tested, and Table 12 summarizes door configuration effectiveness. The smoke generators were secured at 52 minutes.

The results presented in Tables 11 and 12 show that it took approximately 16 to 18 minutes for 75% of the observers to regain visibility of their respective targets. Based on analysis of previous testing in the other hangar bays, and the fact that cold smoke was used during this testing, a door position of El 3 open halfway and El 4 open approximately 1 m (3 ft) would likely provide the best ventilation effectiveness.

TABLE 11. Test 5 Ventilation Effectiveness Per Observer.

Time, min.	Door condition	Observer status, (visibility lost)[a]	Observer status, visibility regained	Ventilation effectiveness, min.
0	Elevator door closed, both port-side doors closed			
30		1, 2, 3, 4, 5, 6, 7, 8		
34	El 3 open 3 ft, El 4 closed		1	4
42	El 3 half open, El 4 open 3 ft		2	12
44	El 3 half open, El 4 open 3 ft		3, 4	14
48	El 3 full open, El 4 half open		7, 8	18
50	El 3 full open, El 4 half open		5	20
52	El 3 full open, El 4 half open		6	22
54	Test end			

[a] Time to visibility lost is taken as time ventilation commenced if visibility was lost prior to opening the hangar bay doors; otherwise it is taken as the actual time visibility was lost.

TABLE 12. Test 5 Ventilation Effectiveness Summary.

Ventilation effectiveness, min.	Visibility recovery, %	Cumulative observer no.	Door condition at recovery
0			Begin test
4	13	1	El 3 open 3 ft, El 4 closed
14	50	1, 2, 3, 4	El 3 half open, El 4 open 3 ft
22	100	1, 2, 3, 4, 5, 6, 7, 8	El 3 full open, El 4 half open

TEST 7 RESULTS (CROSSWIND TEST OF HANGAR BAY 3)

Test 7 was conducted on 22 January 2000 with a 28-knot headwind and an 8-knot port crosswind. Ongoing engineering drills, traffic on the water, and the prevailing winds prevented the ship from achieving a course and speed to minimize the headwind and increase the crosswind. No visibility observers were utilized in this test, and only subjective smoke movement observations were made. The port-side elevator door (El 4) remained closed throughout the test. The starboard-side elevator door (El 3) was opened halfway at 22 minutes. This door arrangement could simulate a scenario where a door could not be opened or did not exist on the port side; thus data from Test 7 are useful in simulating a Hangar 2 crosswind test, a condition not directly tested during the series. Smoke in the general area of the elevator door

opening was swirling around the door opening; however a short distance inside the door (approximately 1.5 m (5 ft)), the smoke was not affected by the door's being opened. Approximately 3 minutes later El 3 was fully opened, with similar observations regarding smoke removal. Other test team members not standing near the elevator door did not notice any smoke movement changes aside from the movement generated by the smoke generators in discharging the smoke. The test was terminated at approximately 40 minutes.

COLD SMOKE LIMITATIONS

It should be noted that the tests conducted onboard the *Eisenhower* used cold smoke rather than hot smoke (which would be produced during an actual fire event). Cold smoke introduced some limitations to the tests because it lacked the buoyancy characteristics of real fire smoke. The density differences between hot and cold smoke are critical for a more detailed evaluation of smoke accumulation and movement within the fire space. During a fire event, ambient air is drawn into the fire compartment at the deck level, passes through the fire (where it is heated), and then is "pumped" up into the overhead. As the smoke layer builds, the hot smoke eventually vents out of the top of the fire compartment and spreads to adjacent compartments. In the presence of a vent opening, strong air currents will develop naturally, drawing fresh cool air into the fire and pumping the hot smoke into the overhead and out of the compartment. Passing through the fire creates the density differences required for the smoke to rise to the overhead and accumulate prior to venting out of the compartment. If no vents are present (i.e., all doors are shut), the smoke layer will build and descend down to the deck, reducing visibility to zero.

Because cold smoke lacks the buoyant forces present in a real fire, it can only be removed by air currents developed by natural or mechanical ventilation. Therefore, in the testing conducted onboard the *Eisenhower*, in the absence of ventilation the cold smoke would have eventually settled in the hangar bay. However during an actual fire event, the buoyant forces generated by the fire are powerful enough to vent themselves, even under still air conditions. Applying this knowledge to the test results, the ventilation times may be reduced. In other words, hot smoke is more efficient at venting itself, especially when no mechanical ventilation is present, as is the case in an aircraft carrier hangar bay. This smoke venting and spread can also work against firefighting operations because the smoke will spread on its own, infiltrating unaffected spaces, degrading visibility, and leading to increased disorientation.

In Australia and New Zealand, all new buildings are evaluated and required to demonstrate satisfactory performance of the installed smoke control systems during a hot smoke test (Reference 8). To perform the hot smoke test, metal fire pans are filled with a predetermined amount of denatured methylated spirits to produce the desired fire size. Methylated spirits are used in lieu of other flammable liquids because of cost, clean combustion byproducts, and low radiation output (there is no visible flame). The metal fire pans are placed within larger water-filled metal pans, which prevent heat transfer from the fire pans to the supporting structure. A smoke generator is positioned near the edge of the fire pans to inject smoke into the hot buoyant plume for dispersal throughout the building. This test arrangement allows for a safe, controlled,

and clean method to evaluate the performance of an installed smoke control system under simulated fire conditions. Such a test may be recommended for future hangar bay testing, depending on the findings of these scoping tests.

CONCLUSIONS

The NATOPS firefighting manual provides guidance for ventilating smoke generated during a fire event in an aircraft carrier hangar bay (Reference 1, Chapter 7). The guidance, in the form of a note, allows for utilizing cross ventilation to facilitate smoke removal. The intent of this guidance is to reduce the heat and smoke threat to the firefighting personnel.

Testing was conducted onboard the U.S.S. *Eisenhower* (CVN-69) to evaluate the effectiveness of opening the hangar bay door approximately 1 m (3 ft) under both crosswind and headwind conditions. Results indicated that irrespective of the ambient wind conditions (headwind or crosswind) and the hangar bay evaluated, opening the elevator door approximately 1 m (3 ft) had minimal effect on reducing the smoke buildup within the hangar bay. Based on these test results, further testing was conducted to determine the most effective door configuration for removing smoke from a hangar bay under various ambient wind conditions (crosswind and headwind) while a fire is burning (i.e., active desmoking).

Based on the test results, a crosswind provided improved ventilation effectiveness compared to a headwind, especially when port-side openings were available. For test configurations with a crosswind and the port-side openings, smoke was removed from the hangar bay in approximately 8 to 10 minutes. Testing with a headwind and open port-side doors resulted in removal of smoke in approximately 16 to 18 minutes. These results apply to Hangar Bays 1 and 3. It was concluded that opening the elevator door approximately halfway would provide the best ventilation configuration while maintaining control over the inflow of fresh air. This conclusion is qualified, knowing that the fire-induced buoyancy of hot smoke would drive the smoke and hot gases out of the compartment. The results for each hangar bay, with the optimal door configuration for the limited number of tests conducted, are provided in Table 13.

TABLE 13. Time to Restore Visibility (75% of Observers).

Hangar bay no.	Crosswind/headwind		Headwind only	
	Optimal door configuration	Visibility restoration time, min.	Optimal door configuration	Visibility restoration time, min.
1	EL 1 half open, port-side doors open	10	El 1 full open, port-side doors open	16
2	El 2 half open (subjective)	Not tested	El 2 half open	>16
3	El 3 half open, El 4 open 1 m (3 ft)	8 to 10	El 1 half open, El 4 open 1 m (3 ft)	16 to 18

The conclusions presented in Table 13 are based on a limited number of tests using cold smoke. Cold smoke does not have any natural buoyancy and, therefore, relies solely on air currents for movement. Therefore the effect of fire-induced buoyancy was not addressed here. The hot smoke will be capable of venting itself out an opening and in certain cases, overcoming the ambient conditions. It is not considered necessary to conduct hot smoke tests in a hangar bay to confirm these results because ventilation effectiveness would likely improve due to the added buoyancy induced during a simulated fire evaluation. Additionally, on-scene personnel would adjust the door configuration to suit the specific fire, to optimize the outflow of hot smoke and gasses with the ambient wind conditions.

RECOMMENDED CHANGES TO NATOPS MANUAL (NAVAIR 00-80R-14, CHAPTER 7)

Considering the test results and conclusions discussed above, recommended changes to Chapter 7 of the NATOPS Manual (Reference 1) have been developed. In order to balance accurate guidance without being overly restrictive to the personnel implementing the doctrine, it is recommended that Section 7.7.7 should read as follows:

7.7.7 Hangar Deck. The following additional procedures for aircraft fires on the hangar deck shall be followed:

Return elevators to the flight deck level.
Close division doors immediately.
Open the starboard-side elevator door halfway. Request the ship to execute a turn in order to position the open door to leeward.
Open windward sponson doors fully or elevator door approximately 3 ft to facilitate venting of smoke.
Leave all hangar deck lights on.
Close all weapons elevator doors and hatches.
All firefighting team members shall don oxygen breathing apparatus/positive pressure breathing apparatus as soon as possible.
Establish background assistance in the adjacent hangar bay.
Post cooling teams on opposite sides of doors of affected bays.
Activate appropriate zones of the hangar bay AFFF sprinkler system for any multi-aircraft fire or when a spill fire is judged to be beyond the capability of the initial hose team.

Because of configuration differences between the hangar bays of aviation capable amphibious ships and aircraft carriers, the test results and conclusions described herein may not be directly applicable to amphibious ships. Therefore, proposed changes to Chapter 8 of the NATOPS Manual for amphibious ship hangar bay firefighting procedures and guidance should be developed based on similar analysis and testing.

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APPENDIX:
TEST EVENT FOR VENTILATION TIME LINES

TABLE A-1. Test 1, Hangar Bay No. 3, Wind Condition Evaluated: Crosswind, Actual Ambient Wind Conditions: 20-Knot Port Crosswind

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
28		4	
34		6	
38		8	
42			
45	El 3 door open 1 m (3 ft)		8
51	El 4 door open 1 m (3 ft)	2	
53	Smoke generators secured		4, 2
54	El 3 door opened fully		
56	El 4 door opened fully		
60	End of test		

TABLE A-2. Test 2, Hangar Bay No. 1, Wind Condition Evaluated: Crosswind, Actual Ambient Wind Conditions: Ambient Wind Not Recorded.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no..
0	Smoke generators on		
24		8	
26		6	
28		5, 7	
30	Elevator door opened 1 m (3 ft)		5
32		2, 1, 4	
34		5, 3, 6	
35	Aft port sponson door opened		
36			5
37	Forward port sponson opened		
40	Elevator door opened halfway		
42			3, 1, 2, 4
46	Elevator door opened fully		7
48		7	7, 8
52		1, 2	
62	Smoke generators secured End of test		

TABLE A-3. Test 3, Hangar Bay No. 1, Wind Condition Evaluated: Headwind, Actual Ambient Wind Conditions: 30-Knot Headwind/10-Knot Crosswind.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
4		2	
6		5, 6	
10		8	
12		4	
16		3	
22		7	
32	Elevator door opened 1 m (3 ft)		
34		1	
38	Port sponson doors opened		1
40			8
42	Elevator door opened halfway		
44		1	
46			3, 7
48	Elevator door opened fully		2, 4
50			5, 6
60	Smoke generators secured End of test		

Note: Test started with residual smoke from previous test, resulting in quick loss of visibility by observers.

TABLE A-4. Test 4, Hangar Bay No. 2, Wind Condition Evaluated: Headwind, Actual Ambient Wind Conditions: 21-Knot Headwind.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
20		8	
22	Power lost in hangar bay	2, 6	
24		1	2
26	Elevator door opened 1 m (3 ft)	7	
30	Elevator door opened halfway	2	7
32	Elevator door opened fully		2, 6
34		4	4
40	End of test		

TABLE A-5. Test 5, Hangar Bay No. 3, Wind Condition Evaluated: Headwind, Actual Ambient Wind Conditions: 20-Knot Headwind/2-Knot Starboard-to-Port Crosswind.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
4		4	
12		3	
16		6	
20		5	
24		2	
26		1	
28		8	
30	Elevator door 3 opened 1 m (3 ft)	7	
34			1
36	Elevator door 4 opened 1 m (3 ft)		
40	Elevator door 3 opened halfway		
42			2
44			3, 4
46	Elevator door 4 opened halfway		
48			5, 8, 7
50	Elevator door 3 opened fully	5	5
52	Smoke generators secured End of test		

TABLE A-6. Test 6, Hangar Bay No. 3, Wind Condition Evaluated: Counter Flow, Actual Ambient Wind Conditions: 28-Knot Headwind/8-Knot Port Crosswind.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
16	Elevator door 4 opened fully		
18	Smoke generators secured		
22	Elevator door 3 opened 1 m (3 ft) End of test		

TABLE A-7. Test 7, Hangar Bay No. 3, Wind Condition Evaluated: Crosswind, Actual Ambient Wind Conditions: 28-Knot Headwind/8-Knot Port Crosswind.

Time, min.	Event	Time visibility lost by observer no.	Time visibility regained by observer no.
0	Smoke generators on		
20	Elevator door 3 opened halfway		
24	Elevator door 4 opened 1 m (3 ft)		
26	Elevator door 3 closed to 1 m (3 ft)		
28	Elevator door 4 opened halfway		
32	Smoke generators secured End of test		

Note: Test began with residual smoke from previous test.